Patent Application of
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for

ENHANCED FOCUSING OF PROPAGATING WAVES BY COMPENSATION FOR MEDIUM ATTENUATION

BACKGROUND OF THE INVENTION

1. Field of the invention

The invention relates to creating images by transmitting signals and sensing the effect of objects in the field of view on the signals.

2. Description of the Prior Art

Ultrasonic, or ultrasound, imaging devices depend on signal wavefronts that propagate into the body. A wavefront can be described by connecting points of equal phase at a given point in time to form a surface that is perpendicular to the direction that ray paths propagate. The wavefront emanates from a transducer aperture and is shaped by a combination of the transducer surface shape and phasing of signals from separate elements of the transducer surface. For focused operation, the wavefront converges to a point, except that diffraction prevents perfect convergence. Successive wavefronts act like new sources of the signal that are ever smaller and closer to the focus point. The reverse process similarly applies to reception where signals from a point source cause a wavefront of spherical shape which is ideally received by a spherical surface receiver. The body of knowledge of wave propagation physics is relied on to refine and extend this concept.

Effective system focusing requires that signal amplitude along the wavefront be well behaved. Problems arise when attenuation is uneven for different paths such that amplitude variations occur along a wavefront. When a coupling fluid is used to allow waves to travel between a transducer and a body it often happens that uneven attenuation situations are set up. As the wavefront propagates through a medium, where the medium is a combination of coupling fluid and body tissue, different paths can undergo

different attenuation processes. Undesirable deviations in amplitude can result. This can change the apparent sidelobe levels. Apparent sidelobes are the actual beam response functions that are caused by the propagation effects in combination with ideal aperture effects. Apparent sidelobes will be simply called sidelobes here. This problem is especially significant for high resolution imaging which depends on large apertures and high frequency signals.

Attenuation means the reduction in signal amplitude other than the reduction that comes from geometric spreading of waves. It is also considered separately from the opposite effect of signal level increase that coming from geometric focusing of waves.

Conventional ultrasound practice tends to involve direct contact of a transducer with the skin. Here the body tissue attenuates signals with uniformity over the ray paths to the degree that body tissue is uniform.

It is known in radio frequency antenna design to control power intensity over the antenna aperture with absorbing materials to achieve the desired radiation pattern. It is also known to taper or weight an aperture, where an aperture is a radiating surface of an array of transducers, to reduce sidelobe response.

In the frequency domain an additional complication is known. This is the fact that there is an extreme variation of attenuation with frequency, according to the rule of about .5 dB per centimeter per megahertz. It is known that this effect also causes degradation of focus. An experiment carried out by Moshfeghi and Waag showed that for excised liver samples, focusing beam width was greater for wide band signals than it was for narrow band signals (Moshfeghi et al., In vivo and in vitro ultrasound beam distortion measurements of a large aperture and a conventional aperture focused transducer).

It is known in ultrasound clinical practice to couple ultrasound signals from transducers to the body by use of a water stand-off. Hitachi Part Number EZU-WL1 is a water bag attachment where the water volume can be adjusted by a syringe. There is a danger with such water filled accessories because the signals at a focus point are not attenuated for shallow operation as they are naturally for deep operation. Although the power levels can be adjusted, it is an action that could be easily forgotten.

Another accessory for oblique stand-off is Hitachi part number EUP-L53ST which is also water filled.

The disclosure of 5,902,748 (5/1999) Madsen et al. describes a water bag to couple ultrasonic signals from a transducer to a phantom where the phantom mimicks tissue. This method couples the maximum power to the focal point but may not satisfactorily control sidelobe response for a variety of phantom shapes.

It is also known to use a tank or bath wherein a fluid couples signals between a transducer and a subject of examination. A coupling fluid means that the fluid serves as an ultrasonic transmitting medium. Water is commonly used as the fluid but a variety of other fluids are used to enable signal coupling. Castor oil is known to match fat for speed of propagation, thus preventing refraction at a boundary. Johnson and Johnson baby oil is also known as a good match for breast tissue. Like water stand-offs in clinical practice, this method couples the maximum amount of power intensity to the focal point but it may not necessarily produce the desired control of sidelobe response.

It is known to produce tissue mimicking materials for use in forming ultrasound phantoms. Patent 5,902,748 (5/1999) Madsen et al. discloses useful recipes for making materials that attenuate and propagate as necessary to represent human body parts. This material is specified to be adjustable to match in detail over a wide bandwidth of frequencies.

It is known in manufacturing of composite materials to vacuum bag an assembly to remove air bubbles and cause flexible surfaces to mutually conform to each other.

Subjects of examination by ultrasound are commonly human or animal. Other uses are known in other fields.

Referenced documents, in entirety, are incorporated herein. They contribute to the description of the present invention, but in case of conflict, the present document takes precedence.

OBJECTS

A general object is to realize maximum resolution benefits of large aperture, high frequency, wide bandwidth, ultrasonic imaging apparatus by utilizing a combination of an attenuation leveling method and a frequency dependent attenuation compensation method. This method provides controlled attenuation over propagation paths so that signals are at desired amplitudes over wavefronts. This would be able to accommodate different human tissue types. The same applies to animal tissue.

An object is to provide a signal transmission method that is generally useful in clinical practice or laboratory experimental procedure.

An object is to provide safety in ultrasound imaging without causing undue reduction in level of transmitted signals from transducers.

An object is to provide flexible surfaces that comfortably conform to body parts.

An object is to provide shallow viewing near the skin surface.

An object is to establish a fairing surface that enables effective scanning by transducer motion.

An object is to establish a fairing surface that simplifies control of signal amplitudes that are transmitted from various transducer elements.

An object is to establish a fairing surface that shapes body parts to an acceptable degree so as to enable variations between subjects to be accommodated.

An object is to enable treatment access simultaneously with real time imaging.

An object is to establish a laboratory method where uniform wavefronts are maintained by using attenuating material to fill in paths between body parts and transducers.

An object is to provide pre-compensation to balance attenuation variations over different paths and frequencies.

An object is to enable sidelobe control using tapered or weighted amplitude distribution functions.

An object is to combine attenuation compensation with lens functions.

An object is to utilize these methods in industrial inspection and other fields that involve wave front propagation.

Further objects of the present invention will become apparent from a consideration of the drawings and ensuing description.

SUMMARY OF THE INVENTION

The invented method involves use of attenuating fluid to maintain a desired amplitude distribution over the surface of a signal wavefront as the wavefront travels between a transducer and a point that is in human tissue and use of compensated signals to cause received signals to have a desired amplitude distribution over the frequency spectrum that describes the received signals. This method further involves a fairing surface, a conformal surface, and special coupling fluid in an arrangement that is devised to convert a human body surface into a surface that is more amenable to high quality ultrasound imaging.

DRAWINGS

FIG. 1 - an apparatus to compensate for tissue attenuation effects.

FIG. 2 - an attenuating safety stand-off with reservoir to maintain attenuation fluid in stand-off pouch.

FIG. 3 - an attenuating safety stand-off with capability to be filled by syringe.

FIG. 4 - an experiment set-up with a tissue mimicking phantom in a tank.

DESCRIPTION OF THE PREFERRED EMBODIMENT

The scope of the invention should be determined by the appended claims and their legal equivalents and not by the examples and variations given. Actual medical practice would be expected to result in many variations of this concept.

This invention involves an interface that can be described as a drum where one end of the drum has a thin rubber sheet fastened to one end of the cylindrical shell of the drum. The other end of the drum has a sheet of Mylar drawn tightly over the other end. The cylindrical shell of the drum is actually a tapered cylinder, that is, a hollow cone. This forms a container that is filled with attenuating fluid that attenuates at the same rate per cm per MHz. as does the body part that is to be examined. Using predictions of this rate, signals are generated that emphasize the frequency spectrum to balance the attenuation effects such that after reception, the intended level spectrum occurs. The rubber sheet conforms to the body part. The Mylar sheet remains planar. A transducer operating outside the drum through the Mylar sheet will produce the same signal amplitude at the focus point regardless of its lateral position. A coupling fluid efficiently transfers signals from the transducer to the Mylar sheet surface. This would be in a container formed on the opposite side of the Mylar sheet. Better control of the wavefront will be achieved by making this coupling fluid an attenuating coupling fluid. This will give a capability to move the transducer axially while still maintaining the same power intensity at the focus point and maintaining the quality of the focus.

Detailed features include a vacuum method to improve adherence and coupling between human skin surfaces and the rubber sheet and fluid pressure control. Both the Mylar and the rubber sheet are thin such that they have no effect on signal propagation.

An immediate system application involves a transducer that is mechanically scanned. This system enables breast imaging where a variety of breast sizes and shapes can be accommodated. Mechanical scanning is facilitated by the fairing surface formed by the taut Mylar sheet.

Another variation is a pre-compensating attenuating pad that allows for variations in the fluid in which the transducer is immersed. Pre-compensation is an uneven way to control attenuation because wavefronts are allowed to be uneven in amplitude over different successive positions and this can give rise to scattering effects.

Variations include use of conventional, hand held ultrasound transducers with fluid filled cushions that are thin walled, rubber pouches that are filled

from a reservoir or with a syringe. In such cases, the fluid is an attenuating fluid such as evaporated milk. Fluids vary to suit the applicable tissue type. Fluids can be gels or other firm or solid materials as desired.

Safety is improved over conventional water stand-off methods since the power level transmitted can be kept at the maximum level needed for deep penetration.

Other variations exclude the fairing function. These include a fluid bath wherein both a transducer and a subject of examination are immersed and the fluid is an attenuating fluid that enables uniform amplitude wavefront.

The invented method provides the process of leveling the effects of attenuation on wavefronts. From a radiating surface **6** indicated in **FIG. 1** to a focus point **18** in the same **FIG. 1** a set of many, evenly distributed paths can be drawn that are called ray paths. The method is to insert materials that may be solid or liquid in way of such ray paths so as to cause uniform attenuation over all such ray paths. Certain tapering of attenuation is also appropriate. The simplest way to insert such material is to allow an attenuating fluid to fill in uneven body terrain where the attenuating fluid is matched in attenuation to the body attenuation. **FIG. 1** also indicates a set of arbitrary waveform generators **101** that produce signals **102** with a device to modify signals **103** to produce pre-compensated signals **104** that are spectrum modified signals. An arbitrary waveform generator is a digital memory based device that contains signal samples that are formed by applying a Fourier analysis to an intended, ideal signal to determine frequency components that are samples of the waveform in the frequency domain. These samples are then modified according to a function that is the opposite of attenuation. An inverse Fourier analysis of the modified signals then yields a time domain signal that balances the attenuation effects of the medium of propagation. These are preparatory steps that are done in advance of actual operation. In actual operation, samples of the time domain signals are then transmitted in bursts by arbitrary waveform generators, as necessary to arrange all the time adjusted signals for transmit beamforming.

A combination of a fairing surface, a conformal surface, and special coupling fluid is devised to convert a human body surface into a surface that is more amenable to high quality ultrasound imaging, with an added benefit of safety. In some forms, the fairing surface is established with a stiff barrier surface. In the simpler forms, the fairing surface is established by the shape

of the transducer face in contact with a flexible membrane. The special fluid couples energy between body and transducer as well as matches the attenuation of human tissue. This is useful where the body surface is uneven or an angle not perpendicular to the skin is desired. It also allows more freedom of movement in searching and optimizing an image, though contact with the stand-off device needs to be maintained.

The preferred embodiment is described here in reference to **FIG. 1**. A skin surface **1** is in close contact with a thin latex rubber sheet **2** which is sealed to a tapered container **4**. Sides of tapered container **4** are tapered to accommodate large aperture illumination. The rubber sheet **2** is shown conformal to the skin **1** even though the body part is irregular as might be a female breast. A Mylar sheet **5** is taut against the opposite end of the tapered container **4**. This tapered container is filled with attenuating fluid **11** such as evaporated milk. Materials would be derived from the body of knowledge, that includes recipes of patent 5,625,137 (5/1999) Madsen et al., for making ultrasound phantoms. A generic transducer **7** is immersed in a coupling fluid **22** contained in upper container **21** to a level **15**, but the coupling fluid can alternatively be an attenuating fluid like the lower attenuating fluid **11**. A transducer radiating surface **6** creates a wavefront that represents a wave signal that represents the transmitted signal. This wavefront propagates toward and converges at a point **18** subject to diffraction limitations. Wavefront convergence is indicated by boundary line **3** along with a like boundary on the opposite side. A pad **20** that represents an attenuating material is used for pre-compensation for coupling fluid **22** that does not attenuate, though it is not needed for coupling fluid that attenuates. The same pad **20** alternately, or in combination with an attenuation function, represents a refracting lens function that operates like curvature and time delay methods to focus beams. The generic transducer **7** moves laterally as indicated by double headed arrow **8** and axially as indicated by double headed arrow **9**. A generic mechanism **14** to mechanically move the transducer is indicated without detail. A sealing device **10** stops air leakage around the skin perimeter and also transfers vacuum around that perimeter. This causes the attenuating fluid to take the shape of the body part with only the thin rubber sheet **2** as a barrier. The rubber sheet **2** is of thickness that is less than one fourth wavelength for ultrasound in that material so it is of negligible ultrasonic effect. The same

rule applies to the Mylar sheet **5**. Attenuating fluid **11** is allowed to freely transfer via tubing **12** between its container **4** and the reservoir **13** where the reservoir is vented at the top to atmospheric pressure.

The illustrated apparatus accomplishes the primary object of this invention because all paths drawn from radiating surface **6** and focus point **18** undergo the same attenuation magnitude.

An added benefit is safety since the power intensity at focal point 18 is the same for all lateral positions of the transducer, in contrast to conventional coupling liquids that do not attenuate. For a water coupling fluid, a An added benefit is safety since the power intensity at focal point 18 is the same for all lateral positions of the transducer, in contrast to conventional coupling liquids that do not attenuate. For a water coupling fluid, very strong signal would occur when the transducer **7** was in the position shown. An added benefit is safety since the power intensity at focal point 18 is the same for all lateral positions of the transducer, in contrast to conventional coupling liquids that do not attenuate. For a water coupling fluid, very strong signal would occur when the transducer **7** was in the position shown. An added benefit is safety since the power intensity at focal point 18 is the same for all lateral positions of the transducer, in contrast to conventional coupling liquids that do not attenuate. For a water coupling fluid, very strong signal would occur when the transducer **7** was in the position shown. An added benefit is safety since the power intensity at focal point 18 is the same for all lateral positions of the transducer, in contrast to conventional coupling liquids that do not attenuate. For a water coupling fluid, very strong signal would occur when the transducer **7** was in the position shown.very strong signal would occur when the transducer **7** was in the position shown.

Part of the purpose of this apparatus is to fair in the natural body shape to create a smooth interface while maintaining quality of focus and apparent sidelobe levels. Comfort to the patient is provided by avoiding direct contact with fluid and avoiding any significant pressures against the body. The vacuum process is benign because the rubber sheet **2** is compliant. The fairing effect of the Mylar sheet **5** means that a larger breast will be slightly pressed down while a smaller breast might not even reach the height of the Mylar sheet **5**. In either case, high resolution imaging would be maintained.

The transducer face **6** is shown with curvature that matches a wavefront curvature that will focus at focus point **18**. In cases where flat arrays are

used and time delay is used to form a wavefront, the attenuation of an attenuating fluid **22** in the upper container **21** will not be correct unless signals from transducer elements are correctly adjusted. This adjustment will vary with different locations of focal point **18** and it is part of the problem of beam steering in general.

The Mylar sheet can be stretched tight over more complicated frames so as to better apply to some body parts. If a frame is rectangular box, open at top and bottom, but two opposite ends of the box are shaped as curved arches, then the stretched Mylar surface will be curved in one dimension and this surface will be like a section of a hollow cylinder. Such design variations are suitable for operation with some transducer designs.

A system design will utilize the methods, forms, and materials described in **FIG. 1** as needed for particular applications.

A simplified variation is a hand held form as illustrated in **FIG. 2**. Here a bladder device made of thin rubber, as specified for the rubber sheet **2** of **FIG. 1**. This apparatus retains the same reservoir **13** and tube **12** as before. The reservoir elevation would be higher than the bladder device **16** to keep most fluid in the bladder **16**. The transducer **7** is now hand held and lateral motions **8** and axial motion **9** are manually carried out. Operation of this arrangement is made flexible because the amount of fluid in the pouch can vary so that contact with the pouch will be maintained for a substantial range of axial motion of the transducer. If electronic system settings are kept unchanged, the image frame can be safely moved in the axial direction as needed and moving across uneven body contours can be safely done.

The hand held method is again illustrated in **FIG. 3**. Here the reservoir is eliminated and the bladder **16** is filled with attenuating fluid through a rubber plug **17** with a syringe. A particular form is implemented using Hitachi Part Number EZU-WL1 with evaporated milk being the fluid that is inserted with the syringe after any water therein is removed. Use of this device as herein modified will prevent accidental use of high intensity ultrasound when using it with a stand off to see shallow features in the body. It will also assure that all ray paths from the transducer face **6** to the focus point **18** are equally attenuated.

When a conventional ultrasound transducer such as illustrated in **FIG. 2** or **FIG. 3** is operated with its associated electronic system the appropriate phase and amplitude control of signals is provided such that imaging is

effective from near the skin down to a particular depth. With the herein disclosed device the same phase and amplitude control would be maintained so the image frame would be displaced to a shallower range of depths and part of the image frame would thus be in the stand off fluid. This can result in viewing in a more effective part of a frame, it can result in the image frame accommodating irregular body surfaces, and it can enable viewing at angles not perpendicular to the skin. Because water does not attenuate signals like body tissue attenuates signals, image signals are not adequately maintained over the aperture and image quality is degraded.

It is appropriate to provide an ultrasound conducting gel to assure continuous contact with the skin. This is desirable, even with the vacuum system in operation. Where this is a thin layer, it is not necessary that this material be an attenuating material. As operating frequencies increase, it will be necessary to evaluate the degree of surface irregularity and to utilize attenuating gel should attenuation leveling be appropriate.

FIG. 4 illustrates an experimental arrangement that illustrates basic principles of the attenuation leveling method as well as an embodiment of the invented apparatus. A glass tank **31** contains a coupling fluid **32** and a transducer array **33** includes a plurality of vertical elements. A circle **34** is a visualization aid to show how the array elements are arranged to focus at a focus point **39** along a vertical line **38**. An abstract body part is depicted by the hemispherical container **37** that is shown as a wire frame model that is enclosed by a thin rubber surface that is the shape of the frame. The body part is called a phantom and it is modeled by filling the container **37** with fluid that acts like breast tissue. The edge ray path **35** travels a shorter part of its route through tissue than does the central ray path **36**. By using coupling fluid **32** that attenuates like tissue, both path undergo the same attenuation. An attenuating coupling fluid is formulated utilizing the same recipes that are disclosed for making tissue mimicking phantoms as given in patent 5,902,748 (5/1999) Madsen et al. This coupling fluid assures that the wavefront that is initially produced by the array of transducers **33** is correctly maintained as it converges to the focus point **39**.

The herein disclosed method and apparatus have utility in any field where attenuation of propagating signals modifies the intensity distribution of signals over the surface of a wavefront and the amplitude of signals over the frequency spectrum.